Applied Thermal Engineering 101 (2016) 390–401

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Experimental investigation of combustion characteristics under different ventilation conditions in a compartment connected to a stairwell

J. Ji *, M. Li, Z.H. Gao *, Y.F. Li, W.X. Shi, J.H. Sun

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, China

HIGHLIGHTS

- A set of burning experiments was conducted in an under-ventilated stairwell.
- Flame behaviors are different with vents opened on the 1st floor and higher floor.
- θ and η can be roughly used to identify whether the fire is ventilation control.
- The degree of under-ventilated increases with the opening height and pool size.
- β with turbulent mixing is compared with previous studies of stack effect.

ARTICLE INFO

Article history:
Received 8 November 2015
Accepted 29 January 2016
Available online 3 February 2016

Keywords:
High-rise building
Ventilation condition
Ghosting flames
Mass loss rate
Temperature attenuation coefficient

ABSTRACT

A set of experiments was conducted in a scaled building model with 12 floors to study the effect of different ventilation conditions on combustion characteristics in a compartment connected to a stairwell with single opening. The results show that when the opening was set at the 1st floor, the upper part of thermal plume inclined to doorway while the lower part inclined to the opposite direction, like a crescent. A special phenomenon, ghosting flame, took place in the experiments where the fire source was relatively large and the opening was set at the 3rd, 6th, and 9th floors, which was considered to be a result of insufficient oxygen supply. The mass loss rate in the current work decreased after the occurrence of ghosting flames. Two parameters θ, which is related to fuel mass loss rate, and η, which is related to the air flow rate at the opening of the stairwell, can be roughly used to identify whether the fire is ventilation control. It is shown that θ increases with the opening height and pool size. The ghosting flames appear at a large degree of under-ventilated condition. There was a stable neutral plane at the opening at the 1st floor, whereas no stable neutral plane was identified at the openings at higher floors. Smoke moving upward depends on turbulent mixing in the stairwell in the current work. Temperature attenuation coefficient with the movement mechanism of turbulent mixing is much higher than that with the movement mechanism of stack effect.

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1. Introduction

Building fires may cause catastrophic casualties and loss of property if not detected before growing into an uncontrollable size. It is of great importance to understand the behavior of thermal plume for the purpose of predicting the impact on structural elements and the dynamics of fire growth [1]. The airflow conditions in the enclosure and weak buoyant plume behaviors in aircraft cargo compartment have been studied [2–7]. But when the fire becomes large and the air supply is less than the stoichiometric requirements, the burning rate is controlled by the air inflow. The fire is in under-ventilated condition [8]. Significant smoke and toxic gas will be produced in under-ventilated conditions. Statistics have shown that smoke is the most fatal factor in building fires, and about 85% fatalities are caused by the hot and toxic smoke [9].

Scholars around the world have conducted a lot of research on under-ventilated fires focusing on mass pyrolysis rates, gas temperatures and spill flames [8,10–12]. Delichatsios et al. [8] proposed a new correlation for predicting enclosure gas temperature and compared it with the MQH (McCaffrey, Quintiere and Harkleroad) correlation. The new correlation was able to predict the gas temperatures in both well-ventilated and under-ventilated fires. Tsai and Chen [10] considered that flashover is a transition from a fuel-controlled fire to a ventilation-controlled fire. The effects of fuel

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* Corresponding authors. Tel.: +86 551 63606431; fax: +86 551 63601669.
E-mail addresses: jijie232@ustc.edu.cn (J. Ji); gaozihe@ustc.edu.cn (Z.H. Gao).

http://dx.doi.org/10.1016/j.applthermaleng.2016.01.117
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sootiness on flashover were determined experimentally. Yamaguchi and Tanaka [11] studied the axis temperature profile of window jet plume in two geometrically similar setups with different sizes. The results showed that if window jet aspect ratios were the same, the non-dimensional temperature was independent of window size and fire temperature but was determined by geometrical conditions. The flame height and heat fluxes of the flame emerging outside of an enclosure were well correlated by two length scales proposed by Lee et al. [12]. The two length scales are related to the effective area of the outflow and the length after which the flow turns from horizontal to vertical due to buoyancy.

However, all previous studies were conducted in a single compartment without connecting to any other structure. In fact, a considerable number of tall vertical shafts have been built in high-rise buildings, such as stairwells, elevator shafts, ventilating ducts and electric cable shafts, which are the most important paths for smoke spreading during fires [13,14]. When smoke flows into the shaft, it will spread upwardly driven by the stack effect which results from density difference between hot air inside and cold air outside or turbulent mixing [15] which is related to the Rayleigh–Taylor mixing process. It will influence the building structure safety and personnel evacuation in the accidents directly. Limited work has been performed to study the effect of the airflow induced by stack effect or turbulent mixing on the combustion characteristics so far. Sun et al. [16] found that the flame inclined toward the staircase due to the fresh air flow induced by the stack effect; However, they did not further explore the combustion characteristics in the compartment. Shi et al. [17] investigated the flame tilt angle and the velocity of airflow sucked into the compartment due to stack effect using a 1/3 scaled model. Their results showed that the flame tilt angle increases inversely with Richardson number and the velocity of airflow sucked into the compartment is proportional to 1/3 power of the heat release rate. Later, they studied the effects of opening height on smoke movement mechanisms and temperature distribution by changing the location of the opening at the 3rd, 6th and 9th floors in the stairwell respectively, and keeping the fire compartment open to the outside [18]. Satoh et al. [19] studied the effect of low-inlet opening position on the direction, angle and length of inclined gas flame using full and reduced scale experiments. The compartments were always exposed to the outdoor directly with sufficient supply of air, creating a well-ventilated condition. However, little attention has been focused on the combustion characteristics at the under-ventilated condition.

In this paper, only one opening was set with varying heights in the stairwell and the fire compartment was not connected to the outside, which is different from the work in Ref. [18]. The effects of opening height on the flame shapes, gas temperature and velocity at the opening as well as mass loss rate were investigated experimentally. This study was undertaken to achieve a better understanding on the characteristics of smoke motion and the flame shapes under different ventilation condition in the emergency stairwell of high-rise buildings. It benefits the current design of smoke management system.

2. Experimental arrangement

The experiments were conducted in a 1/3-scaled stairwell model with 12 floors. To ensure that the results can be extrapolated to full scale, Froude modeling was applied to build up the model which is widely used in fire research [20–23]. For a perfect scaling, all of numbers, e.g. the Froude number, the Reynolds number and the Richardson number, should be kept the same in the model scale as in the full scale. However, in most cases it is not possible and it is often enough to focus on the Froude number. By holding the Froude number constant, the relationships can be simplified to obtain the required scaling laws, which are $\frac{Q_m}{Q_f}=\left(\frac{L_m}{L_f}\right)^{5/2}$, $\frac{m_m}{m_f}=\left(\frac{L_m}{L_f}\right)^{5/2}$, $\frac{u_m}{u_f}=\left(\frac{L_m}{L_f}\right)^{1/2}$ and $\frac{T_m}{T_f}=\left(\frac{L_m}{L_f}\right)^{0}$, where Q is the heat release rate, m is the mass loss rate, u is the velocity, T is the temperature, L denotes the model size and L_m/L_f is the similarity ratio. The subscripts ‘f’ and ‘m’ represent the full and model scale parameters respectively. Froude modeling does not account for conduction and radiation; therefore, the heat transfer mechanisms were predominantly convection [24].

A sketch of the experimental rig is shown in Fig. 1. The ground floor is 1.2 m high and the other floors are 1.0 m high. The cross-sectional sizes of stairwell, atrium and compartment are 1.5 m × 1.0 m, 0.8 m × 0.8 m and 0.8 m × 0.8 m, respectively. There is a window at each floor of the stairwell with a size of 0.9 m high × 0.7 m wide. The first floor has three doors with a size of 0.6 m high × 0.4 m wide connecting the stairwell, atrium, compartment, and the surrounding. Most of the model was made of 2 mm thick steel plates apart from the left and front sidewalls which were made of 12 mm thick fire-resistant glass for observation. The 8 mm thick fireboard was used as the inner lining in the fire compartment and atrium for thermal insulation.

The temperatures of hot gas and ambient air at openings were measured using K-type fine wire thermocouples with a diameter of 1 mm. To account for the measuring error of thermocouples due to the radiation effect, the error between actual hot smoke temperature T_s and thermocouple measured value T_{th} is denoted as ΔT_{error}, which is determined by [18]:

$$\Delta T_{error}=T_s-T_{th}=\sigma\xi_{th}(1-\xi_s)T_s^4/(h+4\sigma\xi_{th}T_s^3) \tag{1}$$

$$h=\frac{Nu\cdot k_g}{D_{th}}=\frac{k_g}{D_{th}}[2+(0.4\mathrm{Re}^{0.5}+0.06\mathrm{Re}^{2/3})\mathrm{Pr}^{0.4}] \tag{2}$$

where σ is the Stefan–Boltzmann constant, ξ_s and ξ_{th} are the emissivity of the smoke and thermocouple junction, k_g is the heat conductivity coefficient of the smoke, and D_{th} is the thermocouple diameter. According to Eqs. (1) and (2), the uncertainty of these thermocouples was within 1.5 °C and the response time is less than 1 s. The radiation error of thermocouple is less than 6% for the typical smoke temperature in this work based on the results of previous theoretical works [25]. The temperature measurement uncertainty of the experiments was approximately 3% through the comparison of three repeated experiments under the same conditions. The total error is 6.7% according to the method from Ref. [26].

The K-type fine wire thermocouples with a diameter of 1 mm were positioned in the fire room and stairwell, as shown in Fig. 1. Three thermocouple trees were set in the vertical cross-section via the fire source, which were 0.1 m (TC1), 0.4 m (TC2), 0.7 m (TC3) away from the right sidewall of the fire room, respectively. The highest thermocouple of each tree was installed 5 cm away from the ceiling and the lower 5 thermocouples were at a 15 cm vertical interval. A thermocouple tree TC consisting of twenty-four thermocouples was set at the centerline of the stairwell, as shown in Fig. 1. Two thermocouples and two hot-wire anemometers (Kanomax, KA12) were positioned at the opening at 20 cm spacing, as shown in Fig. 1. The working temperature of the probes is 5–100 °C and the measurement error is less than 2% [18]. Heptane pool fires were used as fire sources which were located at the center of the compartment on the ground. The square pool is made of 2 mm thick steel board with side lengths of respectively 10 cm, 15 cm and 20 cm and identical depth of 4 cm. The initial depth of fuel in the pool was 2 cm in the experiments. The fuel mass was recorded by a digital electronic balance with a resolution of 0.01 g. A digital Vidicon was used to record the flame shape in front of the fire compartment. The ambient temperature was 15 °C–17 °C. More details can be found in Ref. [27].

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